Appendix C
Applications: Monitoring Schemes for Concrete Dams

C-1. Background

The following study is taken from a report prepared by the US Army Topographic Engineering Center "Design and Evaluation of Geodetic Surveys for Deformation Monitoring at the US Army Engineer District, Seattle." This study of monitoring requirements for Libby Dam illustrates many of the factors that need to be considered in establishing and maintaining a monitoring program.

C-2. Project Description

The Libby Dam project is located in Lincoln, County, Montana on the Kootenai River 17 miles upstream of the City of Libby (USGS 1:24,000 quad map - *Alexander Mountain*). Libby Dam (Figure C-1) consists of 46 concrete monoliths including spillway (monoliths 28-30) and intake (monoliths 20-27).

Figure C-1. Libby Dam.

It has a total length of 880 meters, and a maximum height of about 120 meters. It is classified as having a high downstream hazard potential in the event of failure. The Seattle District, US Army Corps of Engineers designed Libby Dam and its reservoir is used primarily for flood control and power production.

C-3. Reference Network

The reference network (Table C-1) proposed for Libby Dam consists of four reference stations (R1, R2, R3, and R4) on the surrounding abutments, and four stations (C06, C23, C35, C46) located on the crest of the structure on monoliths 6, 23, 35, and 46. Reference station R1 is located on the southwest pillar of the structure enclosing an existing weather station upstream of the dam on the right abutment. Reference station R2 is located on an existing survey observation pillar on the right abutment near the picnic area upstream of the dam. Reference station R3 is located on the left abutment on top of the rock face used for monitoring potential abutment instability. Reference station R4 is an alternate located next to a monumented gravity station near the observation deck on the right abutment. Structure reference points on the upper deck of the dam crest are located at monoliths 6, 23, 35, and 46, each collocated with existing suspended and inverted plumblines. GPS control stations on monoliths 6 and 46 are not collocated with fixed points for the laser surveys. Alignment fixed points could be either re-situated to monoliths 6 and 46, or have measured ties to the plumbline station (i.e., at monoliths 6 and 46).

Table C-1. Approximate NAD83 State Plane coordinates (MT West projection 1602 in meters), for Libby Dam Reference Network.

Station	Northing	Easting	Height
R1	479020.0	170214.0	765.0
R2	478690.0	169884.0	740.0
R3	478010.0	170590.0	838.0
R4	478420.0	169494.0	777.0
C06	478505.0	169771.0	736.0
C23	478315.0	170022.0	736.0
C35	478181.0	170198.0	736.0
C46	478058.0	170360.0	736.0

C-4. Reference Network Reconnaissance

a. General. Photographs of proposed locations for reference stations are shown in Figures C-3 thru C-5. Pillars have been installed for monitoring with conventional instruments, which also appear suitable for GPS occupations, being less than 2 kilometers from the farthest point on the dam crest and acceptable for precision baseline measurement. Monitoring to proposed locations at the top of the left abutment also would be within acceptable range for GPS surveys.

b. Intervisibility study. A study was undertaken of the Libby Dam site to identify zones on the surrounding abutments, and areas upstream and downstream where reference stations could be situated with a direct line-of-sight to the structure. Figure C-2 shows reference station placements that will allow

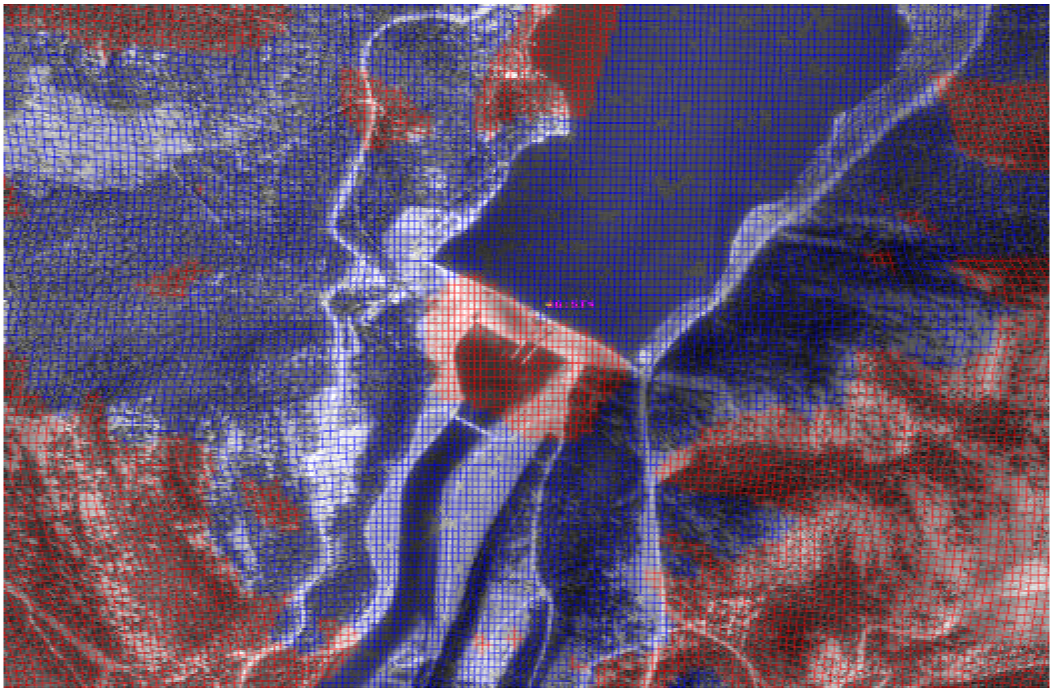

Figure C-2. Intervisibility diagram for reference station placements, blue areas visible, red areas obstructed.

dual-use of GPS and conventional surveying equipment. Blue gridlines represent areas that are visible; red grid-lines represent areas that would be obstructed. The inter-visibility map was developed from a low resolution USGS Digital Elevation Model (DEM), draped with a B/W Digital Orthophoto Quarter Quad (DOQQ) raster image. Although the diagram only meets map accuracy standards, geology and soils maps could be overlain to identify candidate areas for stable reference points.

Figure C-3. Reference Station (R1), Libby Dam.

Figure C-4. Reference Station (R2), Libby Dam.

Figure C-5. Existing survey station, Libby Dam.

C-5. Monitoring Requirements

a. General. Displacements of the dam are related mainly to annual cyclic forces from changes in reservoir elevation and to a lesser extent temperature of the concrete mass. Measured displacements under normal operating conditions are typically no greater than 2 cm in the horizontal plane, and no greater than 0.5 cm in the vertical direction. Both the amount and direction of movement across different structural components (i.e., monolith sections near the powerhouse, spillway, abutment contact zones, foundation areas, etc.) can show a significant and complex variation. Predicting detailed deformations would be difficult without further engineering analysis.

b. Expected deformation and monitoring tolerances. Libby dam is exposed to significant seasonal water level changes of up to 46 m (Figure C-6) and seasonal temperature changes. Data on the expected deformation of the dam is crucial in evaluating instrumentation. Simplified analysis of the expected effects of the changeable pool level was conducted to learn what magnitude of accuracy tolerances should be accepted for designing the deformation measurements.

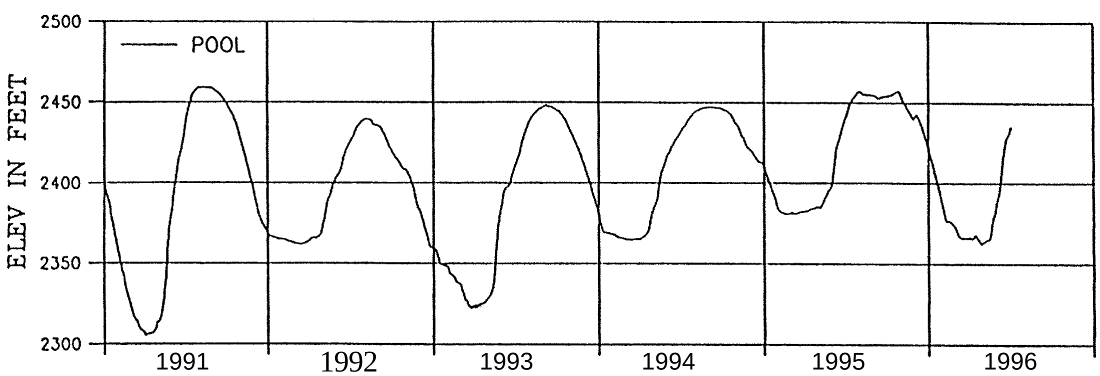

Figure C-6. Water level variations at Libby Dam

c. Deterministic prediction of displacements. The Finite Element Method (FEM) has been used in analyzing a typical cross-section of Libby dam at monolith 23. Figure C-7 shows the FEM mesh and the distortion of the dam when the water load reaches its highest level. As this was a simplified analysis, effects from galleries, penstocks, and other openings were neglected. Since no information on elasticity parameters were available, two FEM analyses of the effects of the changeable water level were performed for two values of the Young modulus:

(1) $E_1 = 15$ GPa
(2) $E_2 = 25$ GPa

with the Poisson ratio kept at:

$\nu = 0.30$.

Figures C-8 and C-9 show the expected tilts of the dam for the maximum (114 m) and minimum (68 m) expected water levels. The results show that the top of the dam (upper gallery) has a maximum total horizontal U/D displacement between:

$\Delta d = -12.5$ mm to $+13$ mm, or 25.5 mm for E_1
$\Delta d = -7.5$ mm to $+8$ mm, or 15.5 mm for E_2

at the center of the dam when the water level changes by 46 m. On average, one may expect a total maximum change of displacements between low and high water levels of about 20 mm. This estimate does not consider the effect of thermal variations of the structure. It may be expected, however, that temperature induced horizontal displacement in the upper gallery would be of a magnitude of very few millimeters, while vertical displacements at the top of the dam could reach about 20 mm (assuming a 20°C maximum change of concrete temperature at the upper levels). The monitoring surveys should be designed to detect:

$(20 \text{ mm} \div 3)/(\sqrt{2}) = 5$ mm displacements at the 95% probability level.

The standard deviation of each positioning/offset component in an individual observation epoch should then be smaller than:

$(20 \text{ mm})/9 = 2.2$ mm.

C-6. Existing Measurement Systems

a. General. Instrumentation is placed in Libby Dam to monitor the structural behavior; ensure safety; determine bending, tilting, and displacement; and check design assumptions and theoretical computations. Instrumentation includes measurement of interior concrete temperatures, joint movements, uplift pressures, structural deflections, and internal concrete stresses. Instruments were also placed in the rock slope adjacent to and above the left abutment for a distance of 2,000 feet upstream to detect movement in the left bank slope. Some measurements are automatically recorded via remote phone line connections and the data are reduced and stored in the District office. A report summarizing the instrumentation evaluations, with data plots, is published twice a year and provided to Operations Division.

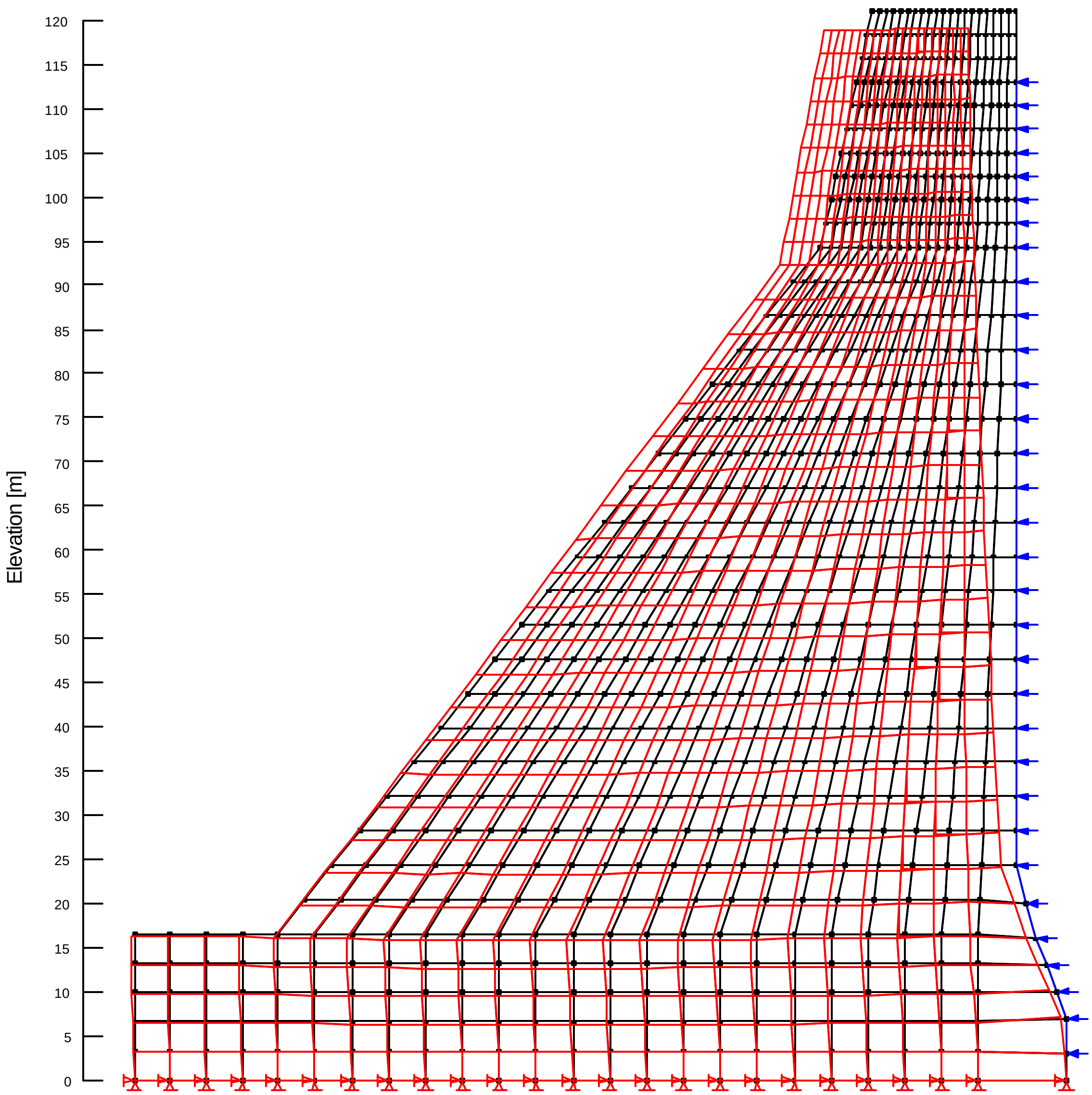

Figure C-7. FEM mesh and displacements (E = 25 GPa, water level = 114 m; displacements 1000 times)

b. Instrumentation. Historical data for all instrumentation readings since 1981 have been published and are updated on an annual basis. Laser alignment surveys are conducted twice a year in the upper service gallery section of the dam. Data for plumblines, uplift pressure cells, drains, and the left abutment are collected monthly with a review for data quality and interpretation made by personnel in District Geotechnical and Environmental Restoration Branch. A geologist reviews left abutment data on a monthly basis and a structural engineer performs a quarterly dam information review.

c. Laser alignment surveys. The existing laser alignment system was installed in 1975 for monitoring the longitudinal alignment of the dam. The lateral offsets of a number of survey points are measured from a baseline established by a laser beam reference. Surveys are scheduled during expected maximum upstream and downstream deflections of the dam indicated by plumbline data.

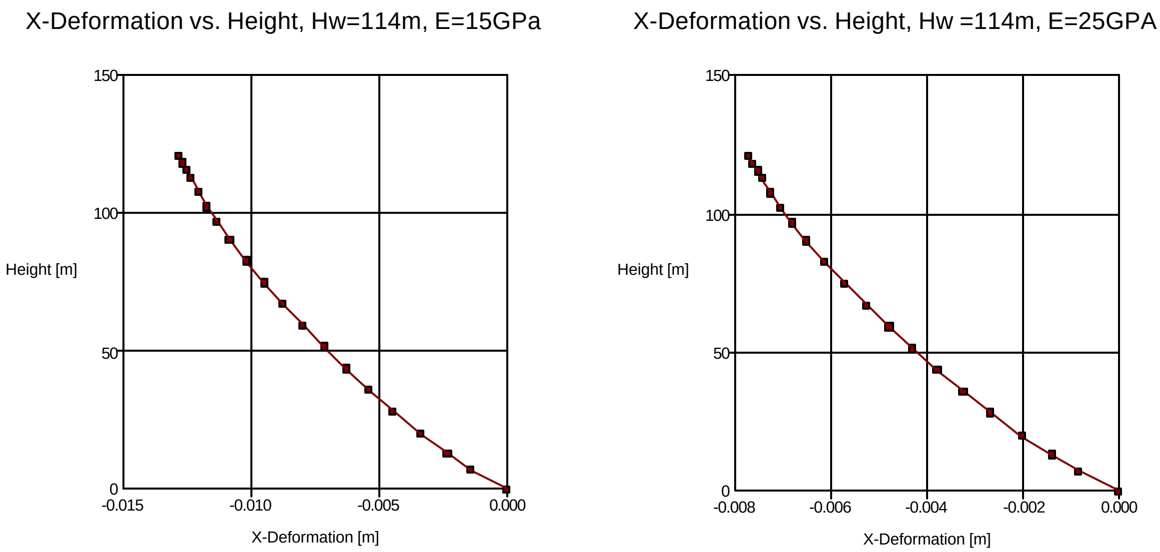

Figure C-8. Displacement due to water load at high pool

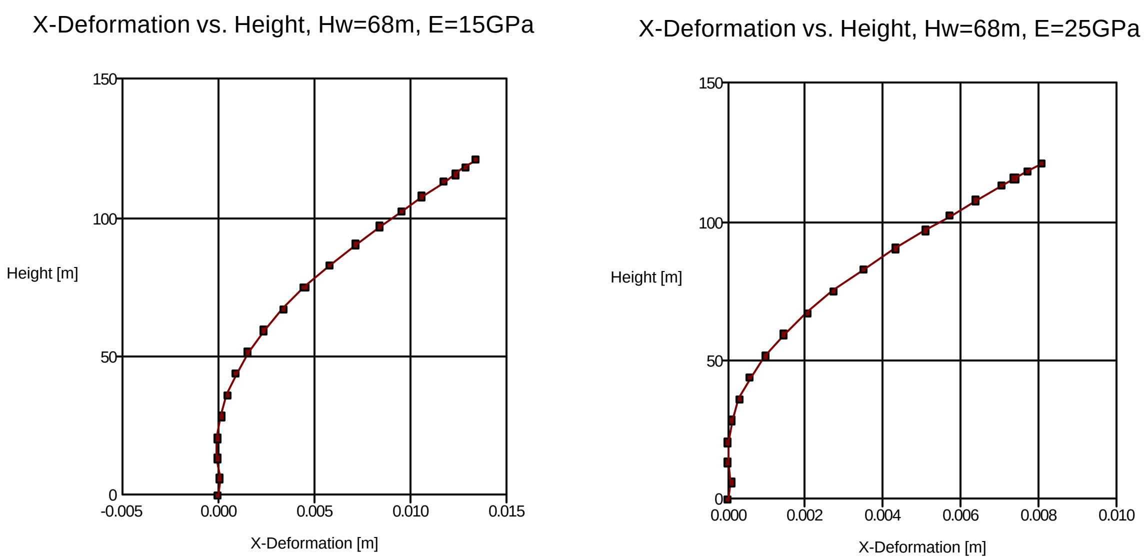

Figure C-9. Displacement due to water load at low pool

d. Inverted and conventional plumblines. Suspended plumblines are installed in monoliths 23 and 35, both are collocated with inverted plumblines set in observation rooms connected to the upper, lower, and drainage service galleries. Inverted plumblines are installed in monoliths 6 and 46, and in monoliths 23 and 35. Until 1975 both sets of plumbline data in monolith 23 showed gradual downstream deflection believed to reflect structural and foundation stabilization. Subsequent data indicates movement is primarily related to reservoir pool and concrete temperature variations. Maximum displacement ranges between 1.5 and 0.5 cm respectively for suspended and inverted plumblines. Isolated lateral movement toward the right bank of approximately 1 mm per year was observed at the base of monolith 35. Inverted plumbline stations are read automatically using optical sensing-reading systems connected to the local data communications network. Plumbline readings since 1991 indicate that both monoliths are stable within "0.25 mm (0.01") in the U/D direction and within "1 mm (0.04") along the axis of the dam.

Monoliths 23 and 35 contain both suspended and inverted plumblines. At each monolith, the suspended plumblines extend from the upper inspection gallery to the drainage and grouting gallery. The inverted plumblines extend from the drainage and grouting gallery to an anchor 10 m deep in the bedrock. Suspended and inverted readings at the drainage and grouting gallery can be combined to give the total displacement of the upper inspection gallery with respect to the bedrock. The combined readings at these two monoliths indicate very smooth cyclic deflections of the dam. Movement is well-correlated with the cyclic water load changes, with a maximum total range of deflections of about 18 mm (0.7").

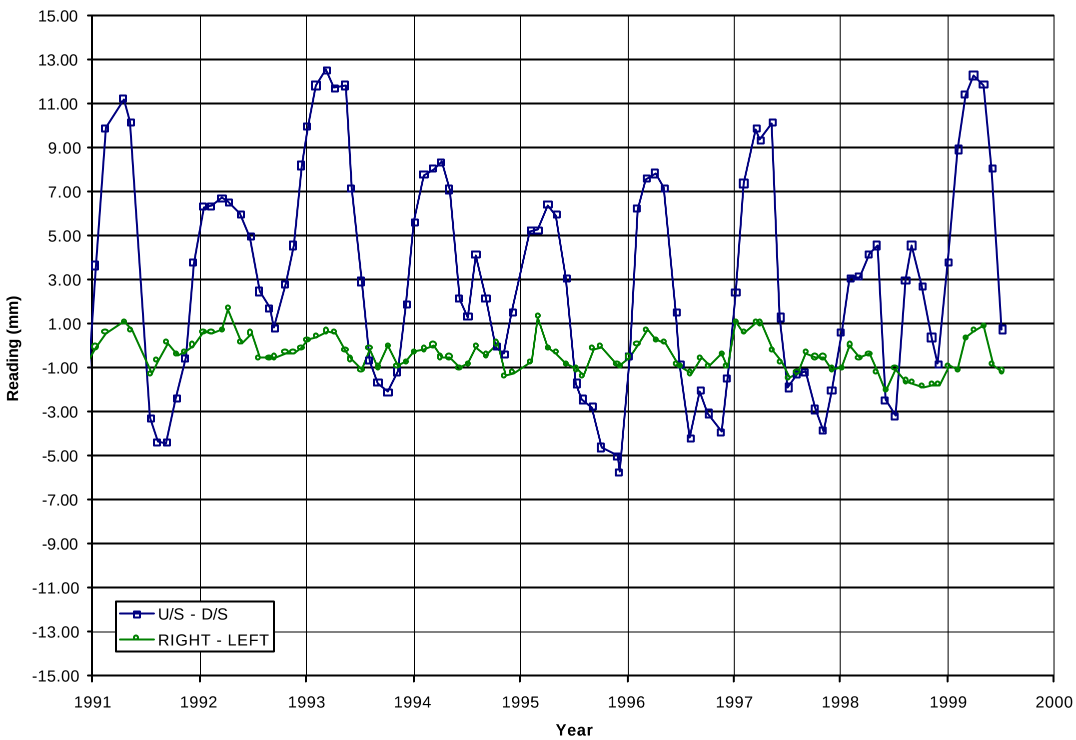

Figure C-10 Combined readouts from suspended and inverted plumblines.

This value agrees well with the predicted FEM value of about 20 mm. Due to the good performance of the plumblines, their data create an excellent control for other instrumentation, particularly alignment and tiltmeter surveys. Plumblines indicate that the maximum U/S deflections occur in March and maximum D/S deflections occur in September, agreeing well with the time of maximum and minimum water levels.

e. Jointmeters. Relative movement across monolith joints is measured by a set of joint meters embedded in concrete. Gauges are located at monolith joints 21/22, 22/23, and 32/33. Annual maximum displacements are on the order of 1-3 mm recorded during spring season. Monoliths adjacent to the left abutment were instrumented in 1992 with an additional twenty, 3D, joint meters to assist in the evaluation of possible deep-seated movement in the left abutment. As of 1995, no significant movement trends have been observed from these gauges.

f. Foundation deformation meters. Downstream of the axis of the dam (10 and 240 feet), deformation meters are installed 10, 20, and 60 feet deep in each of the foundation monoliths 18, 23, and 29. These measured foundation movement during construction and initial impoundment. Currently these meters are read monthly and show only minor movement (1-3 mm cyclic motion correlated to pool elevation).

g. Uplift pressure cells. Uplift pressure cells are installed at the foundation in monoliths 14, 18, 23, 29, 34, and 41. Pressure cells are used to monitor both drainage effectiveness and foundation uplift pressure. Gradients downstream of the grout curtain are reported well below design assumptions.

h. Resistance thermometers. Temperature data to delineate the varying thermal profile through the monoliths is collected infrequently from resistance thermometers installed in monoliths 29 and 33. The stabilized mean ultimate interior temperature of the dam is 44-46 degrees F. Changing water and ambient air temperature mainly causes concrete temperature changes.

i. Strong motion accelerographs. Instruments to record the response of the dam to seismic motion are installed in the dam (2), powerhouse (1), and downstream above the right abutment. No earthquakes have occurred of sufficient magnitude to trigger the instruments.

j. Extensometers. Numerous types of wire and rod extensometers are installed to monitor potential movement in the left abutment nearby a series of rock tendons set after a rockslide that occurred in 1971. X-type (wire) extensometers are used to monitor movement at specific rock joints.

k. Tiltmeters. Tiltmeter stations are collocated with plumblines in monoliths 23 and 35 in the upper and lower service gallery, and in the drainage and grouting gallery. Data from portable and installed tiltmeters are collected on a monthly basis. Automated tiltmeter data from the upper service gallery is collected on a weekly basis from the same elevation as the plumbline reading station. The portable tiltmeter system operates by a vertically oriented, uniaxial, force-balanced, servo accelerometer, with a tilt resolution of 10 arc seconds, assuming measurements are made in two orientations in a horizontal plane (instrument is rotated by 180 degrees between readings).

C-7. Dam and Powerhouse Structure Alignment Surveys

Laser alignment surveying represents a major part of the data collected about the overall behavior of the structure. Surveying provides a comprehensive picture of movement trends and/or anomalies unlike most other types of instrumentation. Alignment offsets are measured at a series of monuments located next to each monolith joint. The reference line is established using a projected laser beam between two fixed points located on monoliths 6 and 46. The laser beam does not directly occupy the alignment reference line during a given measurement campaign. Instead, four separate alignment segments are established between the endpoints of the primary alignment. No information is collected to tie the endpoints of the laser survey to reference monuments in stable areas outside of the structure.

C-8. Abutments and Surroundings

a. Left Abutment. Analysis of several years of instrumentation data suggests that movement is occurring deep within the left abutment rib. Movements define a very large wedge of rock, failing at its toe by rotation and/or deflection slightly upstream and moving along a complex set of joint surfaces. Forces from the main portion of the block projecting into the dam foundation where it could create unacceptable levels of residual stress. Movement of possibly several inches may be necessary before full resistance of the buttress fill is realized. Jointmeters were installed in 1992 to verify that the observed rock movement is not affecting left abutment monoliths. Evaluation of deep seated left abutment movement is not yet complete. Upgraded monitoring of left bank instrumentation is anticipated depending on the results of the completed evaluation. One to several monitoring points could be incorporated into surveying scheme to provide data about surface deformations at the left abutment.

b. Reservoir rim slide activity. Minor erosion, sliding, and isolated areas of rock slope instability along the left bank of the reservoir have been observed. Inspections indicate that the reservoir banks appear to be in good condition and any unstable areas pose no threat to Libby Dam. If the need arises to collect further information on localized settlements or displacements in upstream areas, some additional monitoring points could be incorporated into the survey design.

c. Regional effects. Local tectonic activity and cyclic loading of the reservoir were investigated early on by means of: a regional gravity network; a tiltmeter on the right bank 3 miles upstream; a five station seismic network for microearthquake monitoring; and a trilateration survey network in the vicinity of the dam to monitor horizontal displacements. In years of operation no significant seismicity related to impoundment was exhibited.

C-9. Summary of Instrumentation

The deformation monitoring scheme at Libby consists of two parts: structural monitoring of the dam itself and geotechnical monitoring of the unstable slope at the left abutment. The main deformation monitoring scheme at the dam consists of:

• Suspended plumblines in monoliths 23 and 35 (from the top to the Drainage/Grouting gallery),

• Inverted (floating) plumblines anchored about 10 m into bedrock and extended to the upper gallery at monoliths 6 and 46,

• Inverted (floating) plumblines anchored about 10 m into bedrock and extended to the drainage and grouting gallery where they meet with the two suspended plumblines.

• Laser Alignment System in the upper gallery between monoliths 6 and 46 of a total length of 760 m with two target stations at each monolith.

• Two in-situ installed and one portable tiltmeters in the upper gallery in monolith 35;

• Jointmeters between a number of monoliths.

• In addition, a number of pressure cells, thermistors, piezometers, strong motion accelerographs, and deformation meters with automatic data recording installed in the foundation monoliths are observed. No geodetic observations except the laser alignment system are conducted at Libby Dam. Several borehole extensometers (wire and rod Multi-Point Borehole Extensometer type) are installed and monitored at the slope of the left abutment.

C-10. Upgrades to Gallery Traversing System

a. General. The recent development of precision total stations (e.g., Leica TCA1800 and TCA2003) with self-pointing to corner cube reflectors permits efficient, semi-automatic measurements to a number of targets in a robotic mode. Monitoring deflections of the monoliths using geodetic measurement techniques consists of running a traverse along the center of the inspection gallery. Targets mounted on the monolith walls would be observed from the traverse stations. For maximum reliability and efficiency, the targets should be permanently mounted corner cube reflectors. It would then be possible to use ATR to perform the measurements. With appropriate data collection software, all the observer would have to do at each instrument setup is point the instrument approximately at each target in one round of observations. The total station would then be guided by the data collector to do the rest of the observations on its own.

b. Traversing system configurations. Because the measurements are made from tripod setups, each different survey configurations uses temporary theodolite stations, with control being defined by selected wall targets. Observations are made between adjacent theodolite stations, meaning that the surveys will require up to three tripods and the use of forced centering techniques. Two different possibilities have been considered for providing survey control.

• *Endpoint Station Control.* The first and last monoliths in the survey are considered to be stable. These two monoliths each have three permanently mounted prisms with fixed positions as the only control points in the survey, (a datum bias is introduced if one of the end monoliths is unstable).

• *Plumbline Station Control.* The second method uses plumbline data control, which improves reliability and accuracy. Each monolith with a plumbline will have an additional, permanently mounted, reflector prism serving as control. Movements indicated by the differences in plumbline readings will be introduced as movements of these control points in the adjustment of the survey data.

Three different preanalysis trials were made for the traversing system. The first scheme is shown in Figure C-11, which uses the endpoint monoliths as survey control. Theodolite station spacing is 100 meters, or every 6th monolith, with a theodolite setup in each of the two end monoliths. The second scenario is shown in Figure C-12. It is similar to the first, but 200 m spacing between theodolites is used. The third observation scheme is shown in Figure C-13. It uses 200 m station spacing, but plumbline data is used to control the survey. All scenarios use a standard deviation of 1.0" for direction measurements, 2.0" for zenith angle measurements, and 1.0 mm for distance measurements; these specifications are based on, for example, a Leica TCA1800 total station.

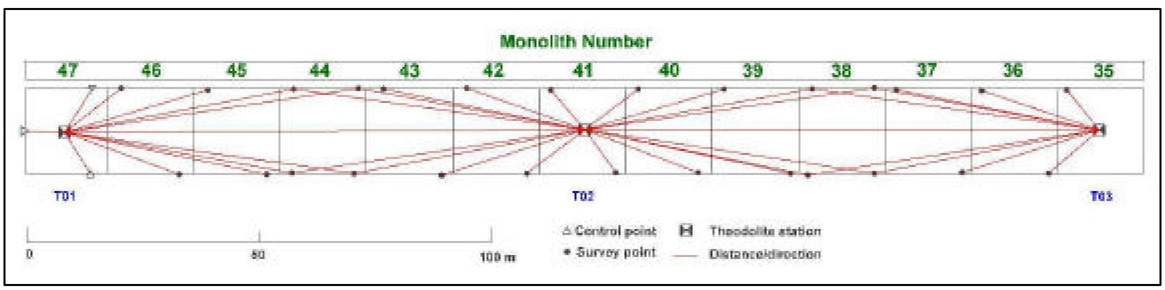

Figure C-11. 3D traverse survey with 100 m station spacing.

Figure C-11 shows a 3D traverse survey with sighting between adjacent theodolite stations. Maximum sight length to target is 60 m requiring 8 instrument setups, and 144 direction, distance, and zenith angle measurements. The largest U/D stream standard deviation is 1.2 mm or 3.3 mm at 95 percent confidence. This configuration gives good results in all three dimensions. The maximum dimension of any error ellipse for a single epoch is 3.0 mm at the 95% confidence level.

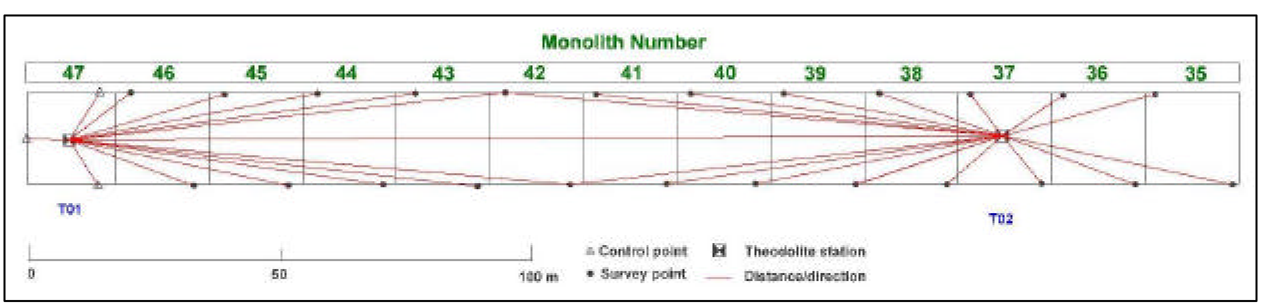

Figure C-12. 3D geodetic survey with 200 m station spacing.

Figure C-12 shows a 3D traverse survey with sighting between adjacent theodolite stations. Maximum sight length to target is 100 m requiring 5 instrument setups, and 99 direction, distance, and zenith angle measurements. The largest U/D stream standard deviation is 1.4 mm or 3.8 mm at 95 percent confidence. This configuration requires considerably less work than the survey with 60 m station spacing, with slightly lower precision.

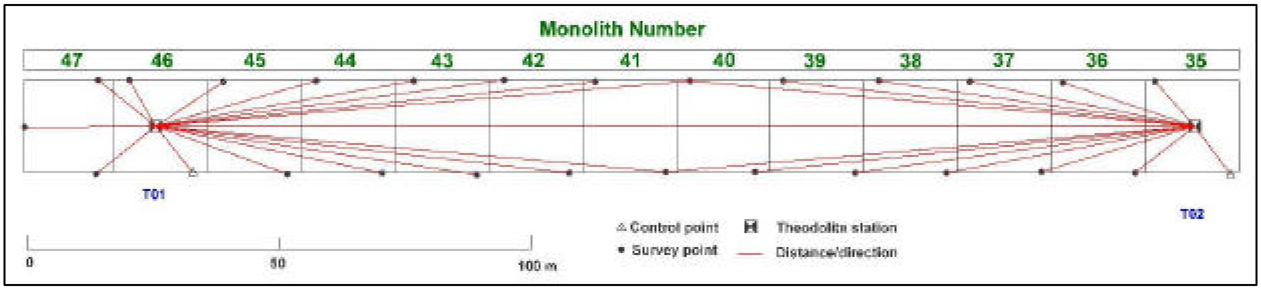

Figure C-13. 3D geodetic survey with 200 m station spacing and plumbline control.

Figure C-13 shows a 3D traverse survey with sighting between adjacent theodolite stations. Maximum sight length to target is 100 m (with plumbline control) requiring 6 instrument setups, and 108 direction, distance, and zenith angle measurements. The largest U/D stream standard deviation is 0.7 mm or 1.8 mm at 95 percent confidence. This configuration gives much better results than the other schemes because of the plumbline control distributed at points along the traverse. The survey using 200 m station spacing and plumbline control is the preferred alternative. It provides excellent precision, with a manageable number of observations. The observation effort could be further reduced by using only one target per monolith. It would then be very easy to complete the survey in a few hours by one observer.

C-11. Upgrades to Other Instrumentation

a. Plumblines. Suspended and inverted plumblines are among the most reliable types of instrumentation that can be used for the measurement structural displacement and tilt. Data from the suspended and inverted plumblines should be combined to yield displacements of the top of the suspended plumbline with respect to the anchor of the inverted plumbline. It would also be possible to monitor the movement of the suspension point by performing GPS measurements on the deck immediately above the plumbline.

b. Tilt measurements. Tiltmeters should be carefully calibrated for thermal and temporal drift. Changes in structural tilt indicated by the plumbline readings are of the order of 30 arc-seconds (variation of approximately 18 mm at monolith 23, with a distance from the anchor point of 120 m assumed).

c. Geodetic leveling. The level of observed changes in tilt given by the plumblines could easily be detected by using geodetic leveling. A good-quality geodetic level and careful observation procedures should be capable of determining height differences with a standard deviation of 0.1 mm. If the survey benchmarks are located a distance of 4 m apart, this gives an angular precision of 5 arc-seconds for a single survey. Tilt differences would be determined with an accuracy of:

$$(5)(1.96)(\sqrt{2}) = 14 \text{ arc-seconds.}$$

Tilt differences could be evaluated in both the upstream/downstream and left/right directions, as indicated in Figure C-14. This gives leveling a decided advantage over tiltmeter measurements, which have a stated standard deviation of 10 arc-seconds and need frequent calibration.

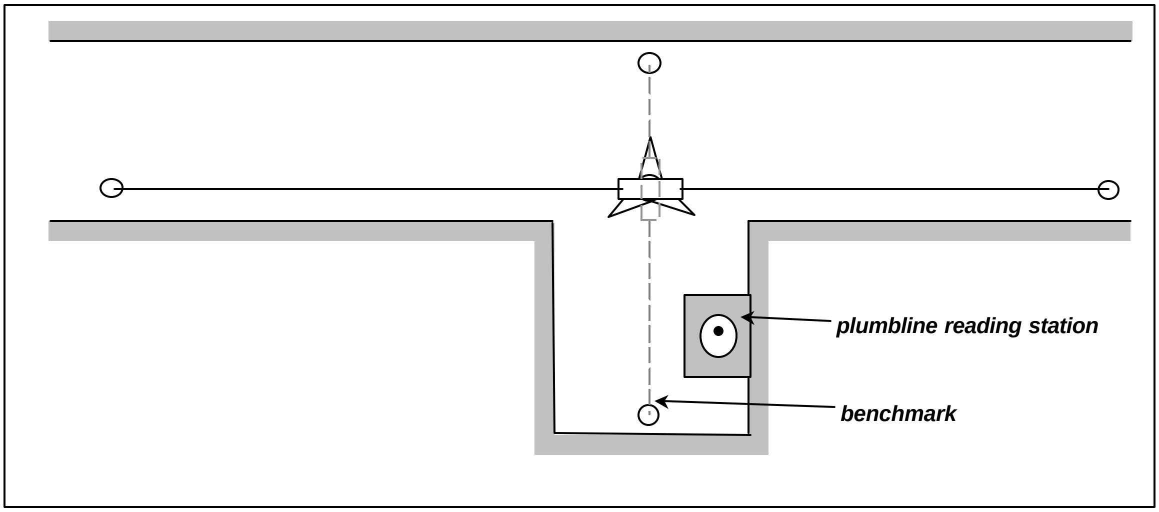

Figure C-14. Tilt measurement with a geodetic level.

d. Vertical movement within galleries. Monitoring schemes are primarily concerned with upstream/downstream structural movements. However, seasonal variations in water level and temperature can result in vertical structural movements as well, possibly with a greater magnitude than the upstream/downstream deflections. Instrumentation can provide verification of the expected vertical movements and/or structural expansion. Determination of vertical structural movements, and an evaluation of possible structural expansion, can be accomplished if an observation scheme is implemented as shown in Figure C-15. Within each gallery, a survey benchmark can be installed on each monolith to be monitored. Measurements in an individual gallery will yield the relative vertical displacements between monoliths at the gallery height.

e. Vertical movement between galleries. To determine the relative height changes between the different galleries (caused by expansion of the structure), a suspended invar wire with attached scales is used. At each gallery, the scale is observed along with the benchmarks. A change in height difference between the scale and a nearby benchmark (located in the same monolith) represents the change in height between the benchmark and the wire suspension point. This is valid only if the wire has a much lower coefficient of thermal expansion than does the structure, and this is why invar wire should be used.

f. Vertical movement between the dam and bedrock. The inter-gallery changes in height differences are all made with respect to the structure itself. To determine whether or not there is a rigid-body movement of the structure with respect to the underlying bedrock, an Multi-point Borehole Extensometer (MPBX) is installed near the lowest reading station. This MPBX must have anchors deep in the bedrock. If the height differences from the wire scale to the MPBX reference plate are combined with the MPBX readings, the change in height difference can then be derived for any of the wire scales with respect to the bedrock and thus for any of the gallery benchmarks with respect to the bedrock.

C-12. Upgrades to Geodetic Surveying Systems

Conventional geodetic surveying and GPS surveying systems are proposed for positioning points on the upper deck of the dam crest (Figure C-16). Representative preanalysis trials and measurement schemes developed for these surveys are illustrated in the Figures C-17 and C-18.

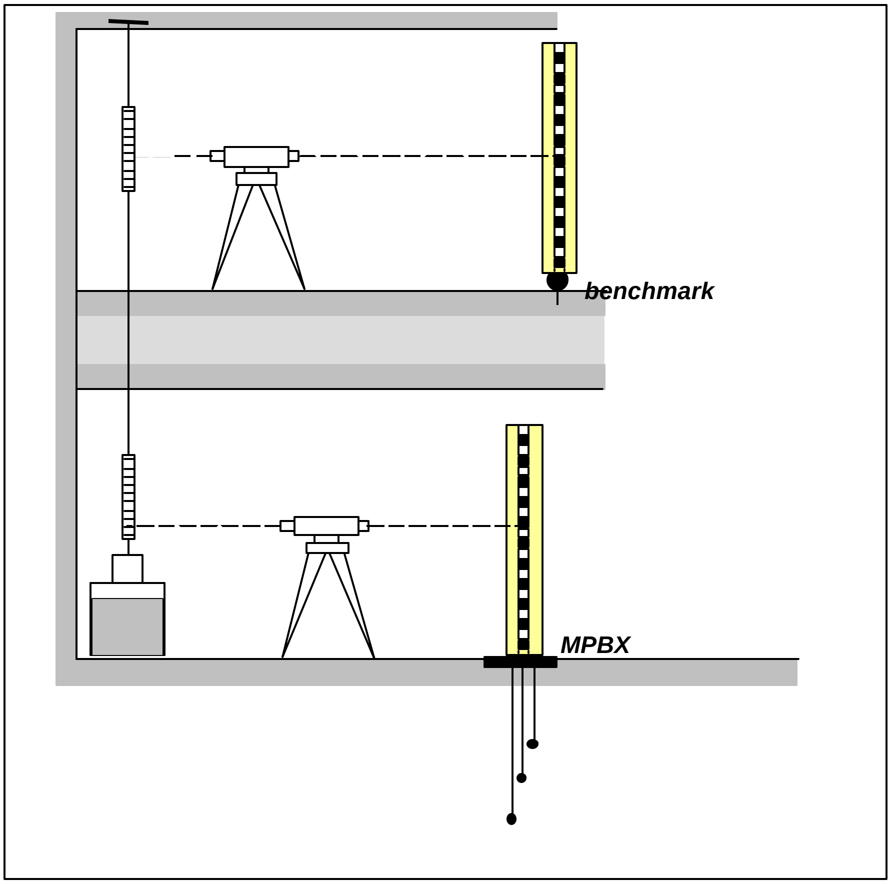

Figure C-15. Measurement of vertical structural expansion with invar wire.

C-13. Schematic Design of Monitoring

a. Reference network. Area monitoring network consists of 4 GPS stations with:

- 2 GPS stations in a stable area within one kilometer from the dam (downstream areas may generally be more stable);

- Optionally, 1-2 GPS stations at the unstable slope to provide control for the results coming from the borehole extensometers.

b. Structure control network. Structural monitoring network consists of:

- 2 GPS stations at the upper deck on monoliths 6 and 35, supplemented (if needed) by two survey stations (pillar type with the self-centering plates) at monoliths 23 and 46 to connect the network with the plumblines in those monoliths;

c. Localized networks. Local Structural monitoring consists of:

• GPS or conventional geodetic surveys across the crest of the structure, or geodetic traversing in the upper service gallery, between plumblines at monoliths 6, 23, 35, and 46;

• Leveling between monoliths 6 to 46 with one benchmark in each of the intermediate monoliths.

• Existing (four) inverted and (two) suspended plumblines;

• Existing jointmeters;

• One vertical invar wire extensometer with leveling scales at the upper gallery, lower gallery and in the drainage gallery;

• One vertical borehole rod extensometer (MPBX type) in the drainage gallery, with three rods of 5m, 10m, and 15 m in the bedrock (if possible);

• Existing borehole extensometers at the face of the unstable slope;

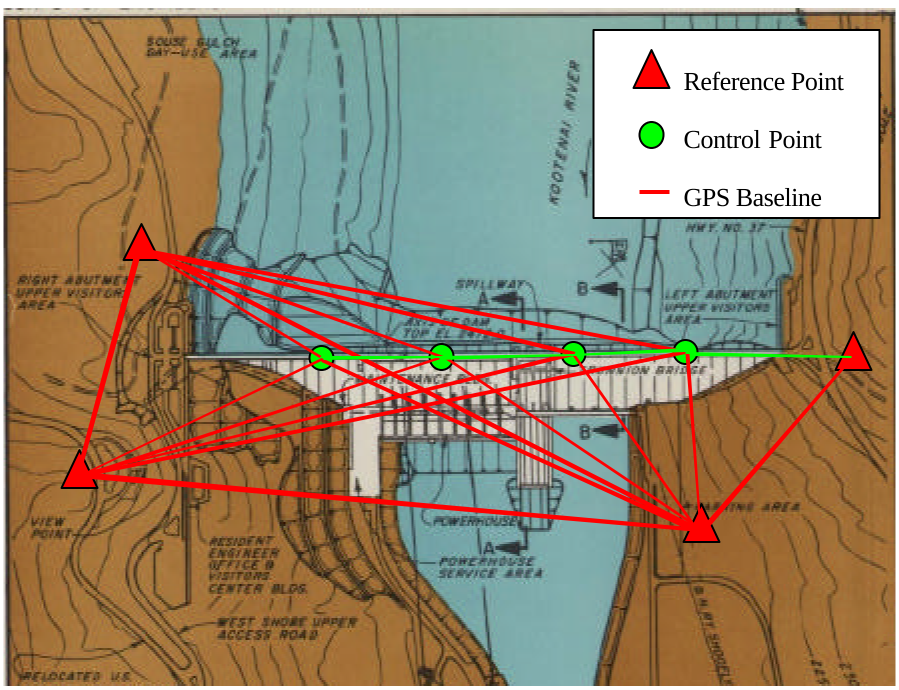

Figure C-16. Schematic Plan of monitoring survey

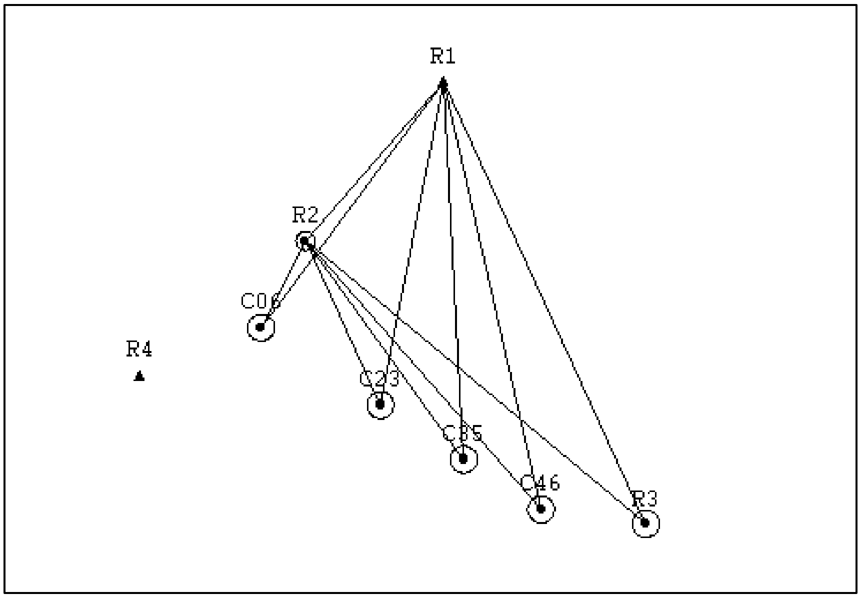

Figure C-17. GPS Reference Network Preanalysis

Largest Position Error: 2.0 mm
Number of Stations: Total 5 (1-fixed and 4-unknown)
Number of Setups: 5 Occupations (Stations R1,R2,R3,C06,C46)
Number of Observations: 33 measurements
Repeated Observations: 2 (baselines)
Instrument: Geodetic Quality GPS receiver

2-D and 1-D Station Confidence Regions (99.000 percent):

STATION	MAJOR SEMI-AXIS (m)	VERTICAL (m)
C06	0.0020	0.0017
C23	0.0020	0.0017
C35	0.0020	0.0017
C46	0.0020	0.0017
R2	0.0014	0.0012
R3	0.0020	0.0017

Comments: Reference network surveys using only GPS systems. Survey scheme meets accuracy requirements using additional ties to points located on the structure.

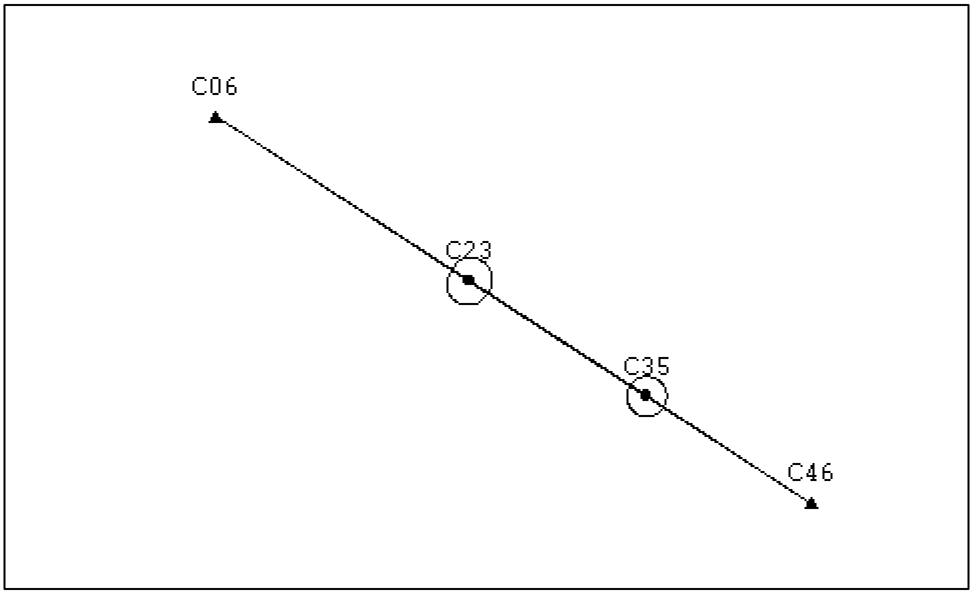

Figure C-18. Structure Control Network

Description: Structure Network
Largest 2D Position Error: 3.1 mm
Number of Stations: Total 4 (2-fixed and 2-unknown)
Number of Setups: 4 Occupations (C06,C23,C35,C46)
Number of Observations: 20 measurements
Repeated Observations: 2 (repeated sets)
Instrument: Total Station

2-D and 1-D Station Confidence Regions (99.000 percent):

STATION	MAJOR SEMI-AXIS (m)	VERTICAL (m)
C23	0.0031	0.0155
C35	0.0026	0.0113

Comments: 2-point structure control network on dam using only conventional surveys. Survey scheme ties the plumbline stations with observations from traversing only between endpoints. The survey meets accuracy requirements. Forced centering is used to reduce centering error in angle measurement.